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Vermeiren

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(54) **IMPLANTABLE AUDITORY PROSTHESIS WITH FLOATING MASS TRANSDUCER**

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(22) Filed: **Oct. 19, 2015**

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H04R 25/00 (2006.01)

(52) **U.S. Cl.**
CPC ***H04R 25/606*** (2013.01); *H04R 2225/67* (2013.01)

(58) **Field of Classification Search**
CPC H04R 2225/67; H04R 25/606
See application file for complete search history.

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(74) *Attorney, Agent, or Firm* — Edell, Shapiro & Finnan, LLC

(57) **ABSTRACT**

Embodiments of the present invention are generally directed to an implantable auditory prosthesis that comprises a transducer configured to be implanted in a recipient. The transducer comprises at least one bender element (e.g., piezoelectric element, magnetorestrictive element, etc.) that is configured to deform in response to application of an electrical signal thereto so as to generate vibration for delivery to the recipient. One or more components are mechanically and electrically connected to the bender element and are configured to generate additional vibration for delivery to the recipient. In certain embodiments, the one or more components mechanically coupled to the bender element comprise an inductor coil operating as a counter-mass. The inductor coil may be configured to drive another mass (e.g., a magnet) so as to operate as an active vibration generation system.

20 Claims, 6 Drawing Sheets

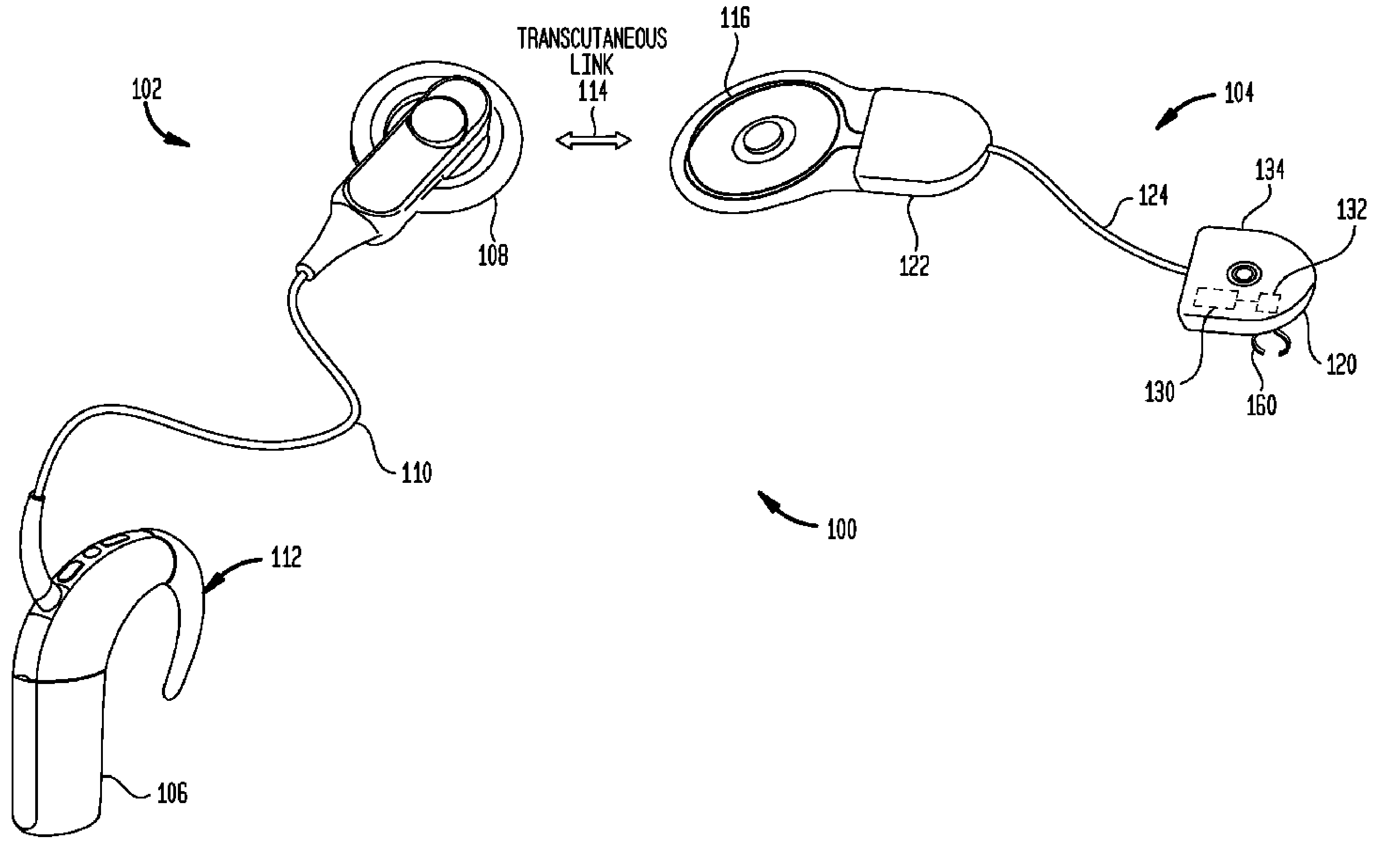

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FIG. 1

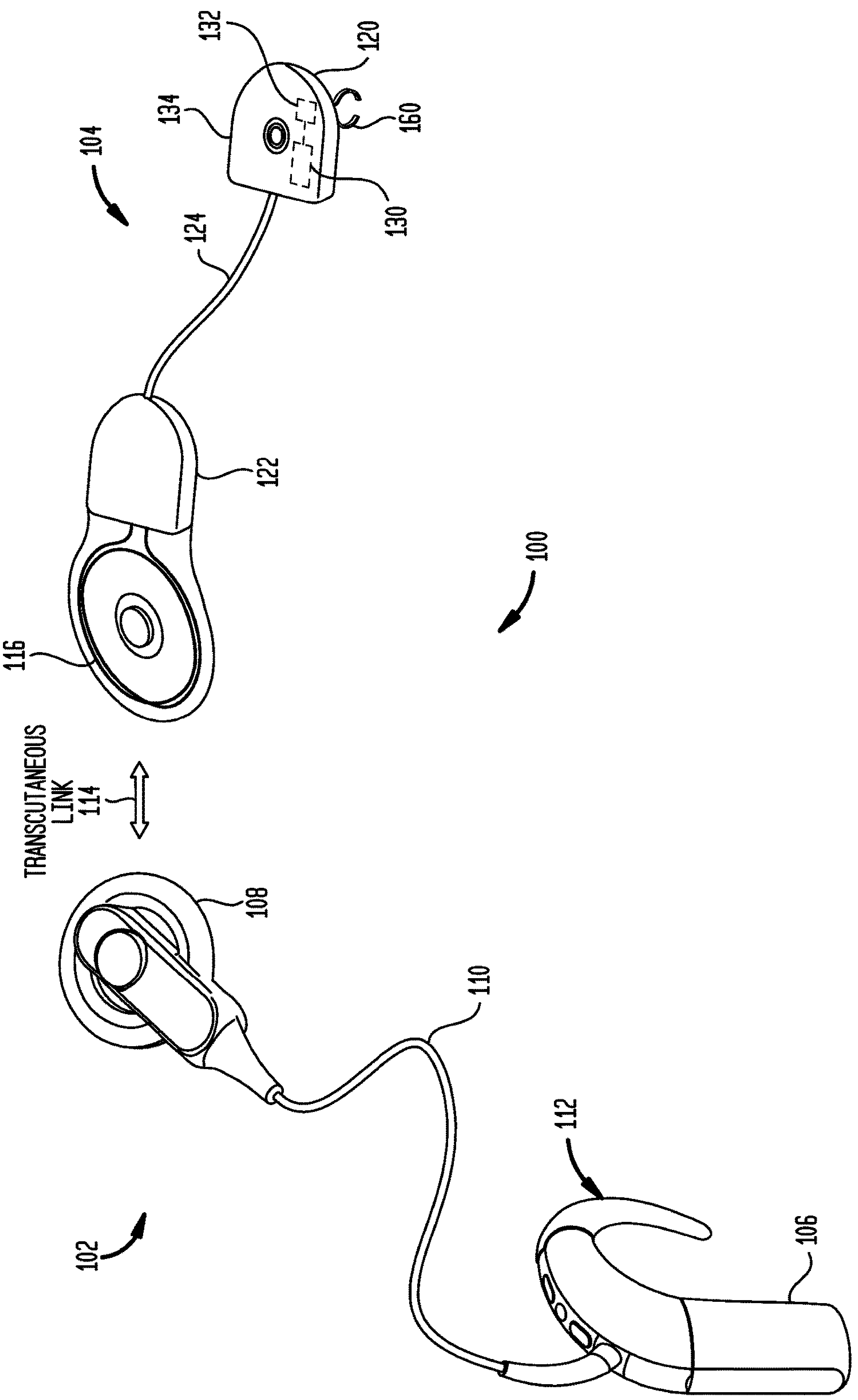

100
102
104
106
108
110
112
TRANSCUTANEOUS LINK 114
116
120
122
124
130
132
134
160

FIG. 2

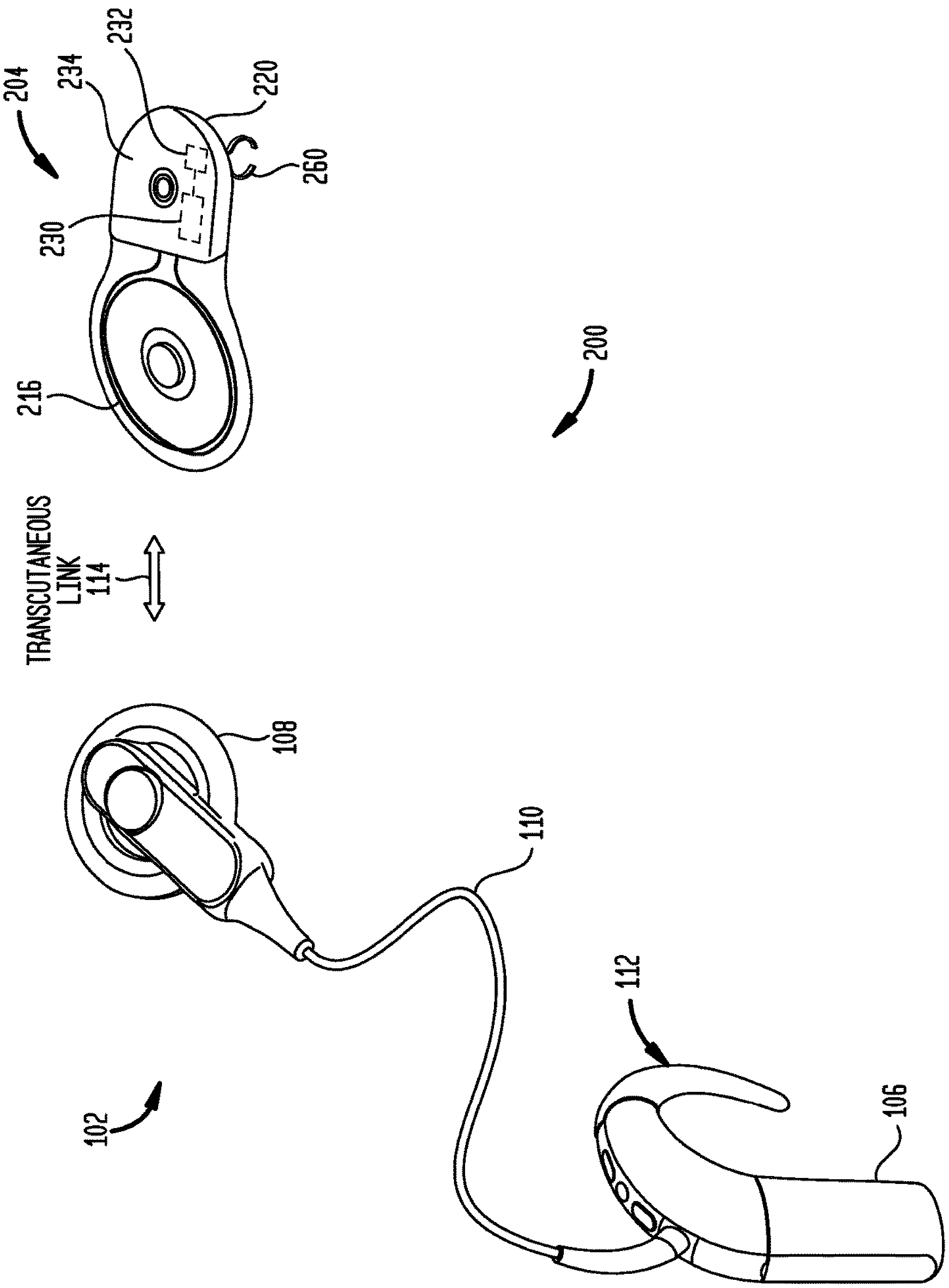

204
234
232
220
260
230
216
200
TRANSCUTANEOUS LINK 114
108
110
112
102
106

FIG. 3

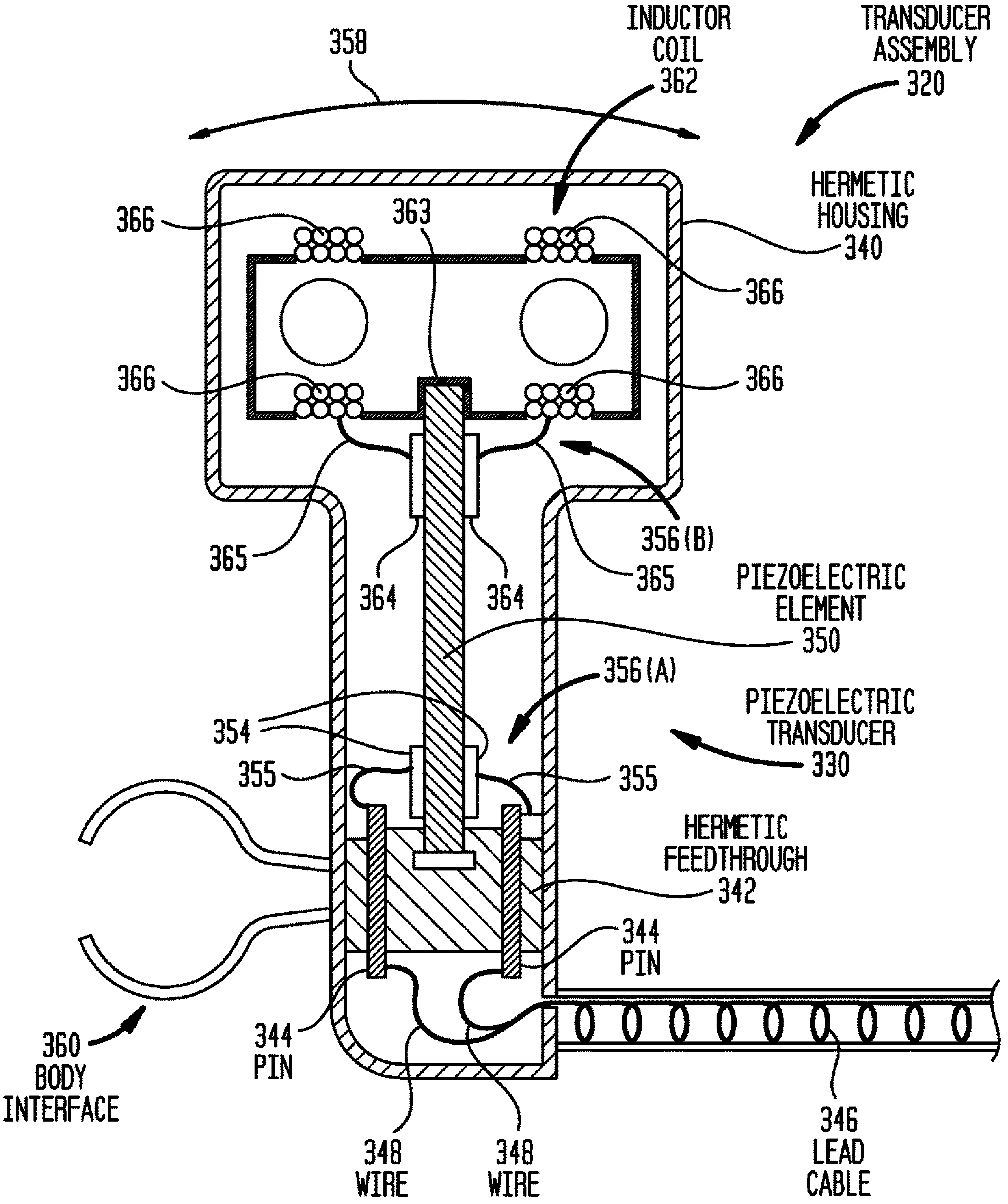

358
INDUCTOR COIL 362
TRANSDUCER ASSEMBLY 320
366
363
HERMETIC HOUSING 340
366
366
366
365
364
364
356(B)
365
PIEZOELECTRIC ELEMENT 350
356(A)
354
PIEZOELECTRIC TRANSDUCER 330
355
355
HERMETIC FEEDTHROUGH 342
344 PIN
360 BODY INTERFACE
344 PIN
348 WIRE
348 WIRE
346 LEAD CABLE

FIG. 4

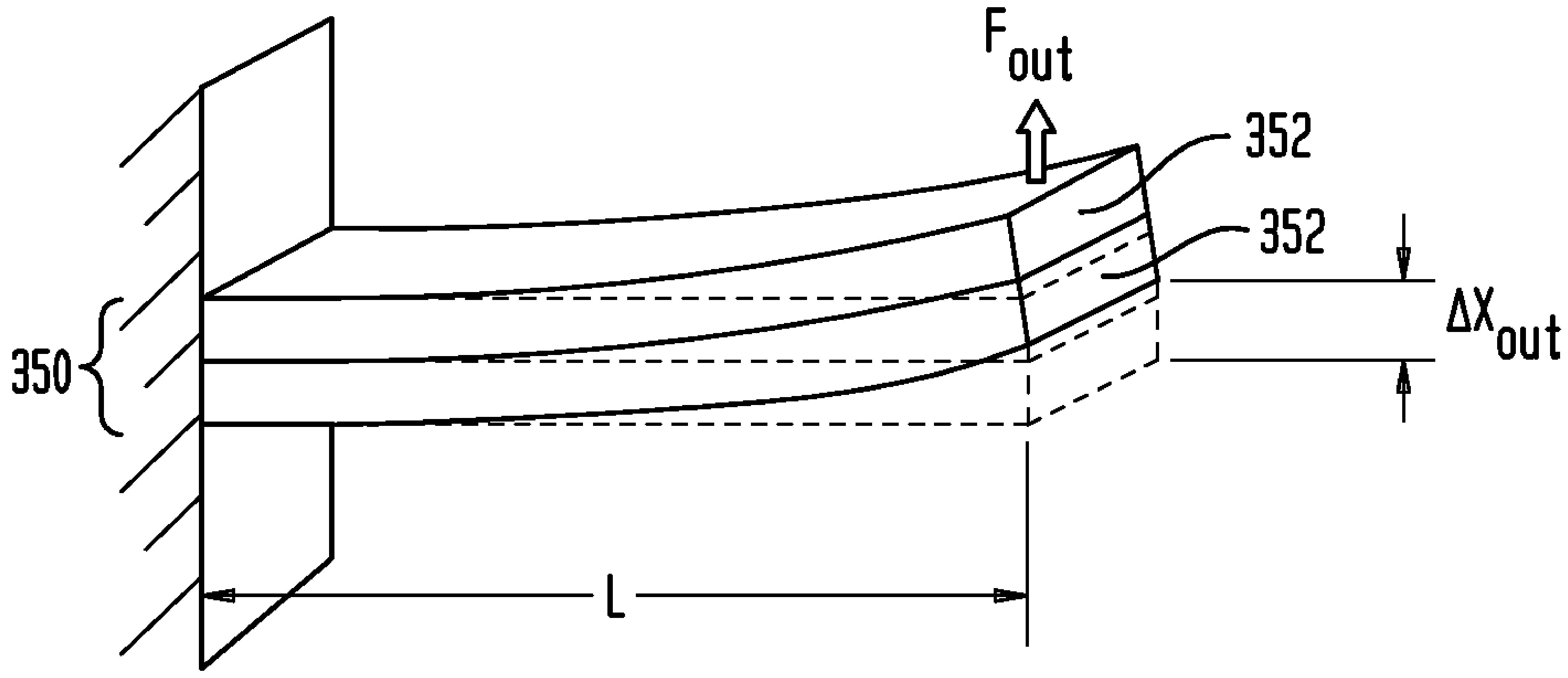


FIG. 5

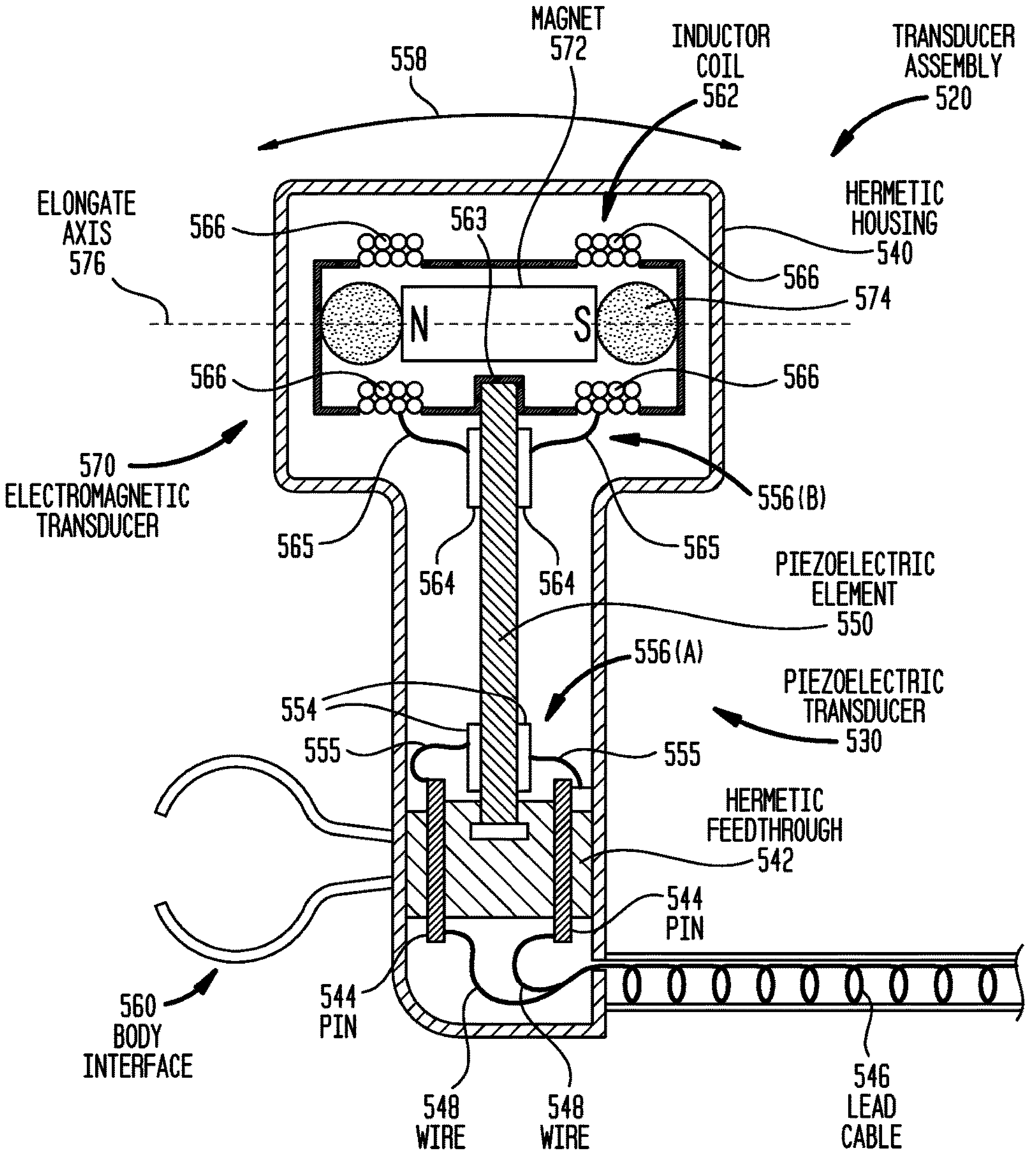
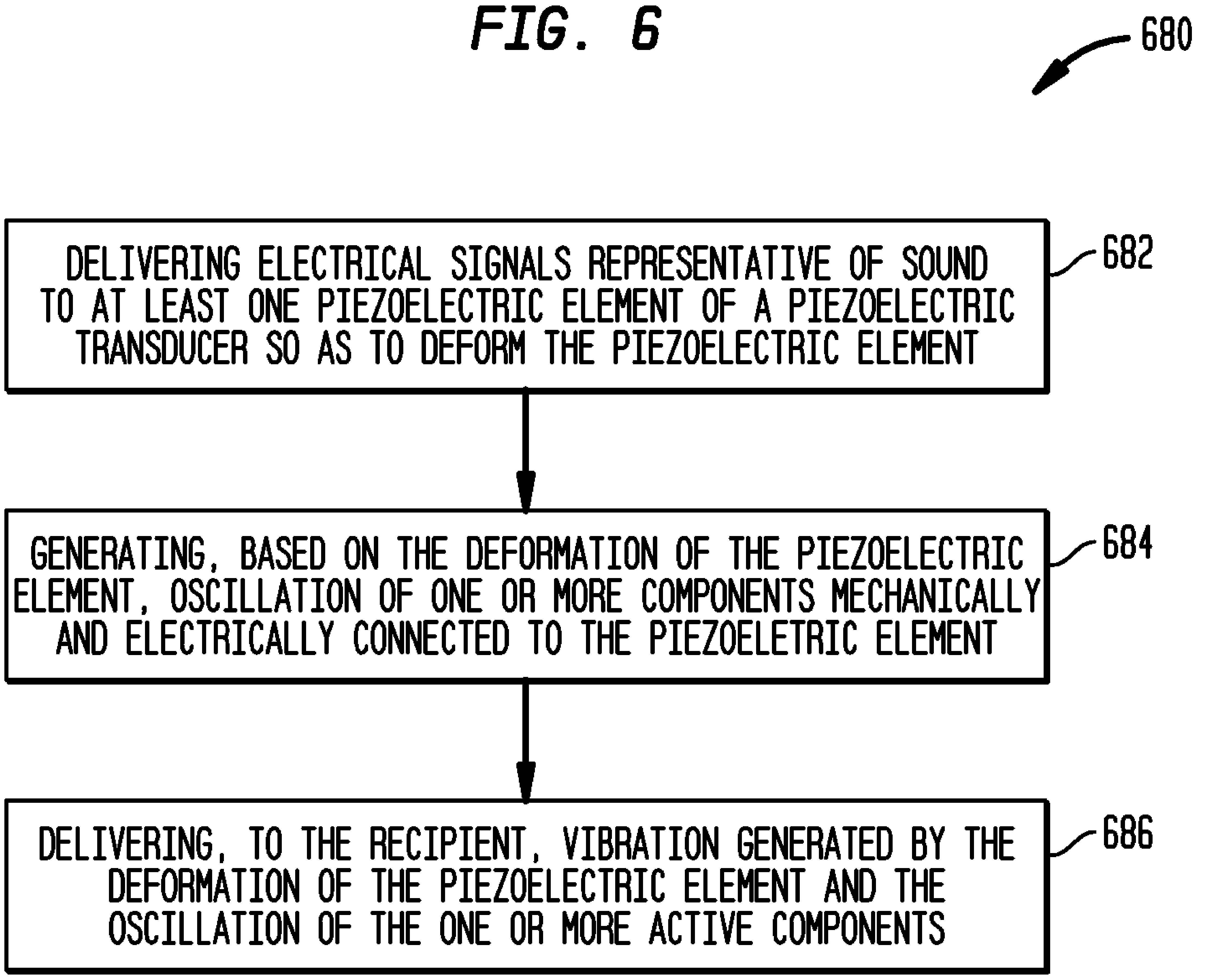

558
MAGNET 572
INDUCTOR COIL 562
TRANSDUCER ASSEMBLY 520
ELONGATE AXIS 576
566
563
HERMETIC HOUSING 540
566
574
N
S
566
566
570 ELECTROMAGNETIC TRANSDUCER
556(B)
565
564
564
565
PIEZOELECTRIC ELEMENT 550
556(A)
PIEZOELECTRIC TRANSDUCER 530
554
555
555
HERMETIC FEEDTHROUGH 542
544 PIN
560 BODY INTERFACE
544 PIN
548 WIRE
548 WIRE
546 LEAD CABLE

FIG. 6


680
DELIVERING ELECTRICAL SIGNALS REPRESENTATIVE OF SOUND TO AT LEAST ONE PIEZOELECTRIC ELEMENT OF A PIEZOELECTRIC TRANSDUCER SO AS TO DEFORM THE PIEZOELECTRIC ELEMENT
682
GENERATING, BASED ON THE DEFORMATION OF THE PIEZOELECTRIC ELEMENT, OSCILLATION OF ONE OR MORE COMPONENTS MECHANICALLY AND ELECTRICALLY CONNECTED TO THE PIEZOELETRIC ELEMENT
684
DELIVERING, TO THE RECIPIENT, VIBRATION GENERATED BY THE DEFORMATION OF THE PIEZOELECTRIC ELEMENT AND THE OSCILLATION OF THE ONE OR MORE ACTIVE COMPONENTS
686

IMPLANTABLE AUDITORY PROSTHESIS WITH FLOATING MASS TRANSDUCER

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims priority to U.S. Provisional Application No. 62/065,837 entitled "Implantable Auditory Prosthesis with Floating Mass Transducer," filed Oct. 20, 2014, the content of which is hereby incorporated by reference herein.

BACKGROUND

Field of the Invention

The present invention relates generally to implantable auditory prostheses.

Related Art

Hearing loss, which may be due to many different causes, is generally of two types, conductive and/or sensorineural. Conductive hearing loss occurs when the normal mechanical pathways of the outer and/or middle ear are impeded, for example, by damage to the ossicular chain or ear canal. Sensorineural hearing loss occurs when there is damage to the inner ear, or to the nerve pathways from the inner ear to the brain.

Individuals suffering from conductive hearing loss typically receive an acoustic hearing aid. Hearing aids rely on principles of air conduction to transmit acoustic signals to the cochlea. Typically, a hearing aid is positioned in the ear canal or on the outer ear to amplify received sound. This amplified sound is delivered to the cochlea through the normal middle ear mechanisms resulting in the increased perception of sound by the recipient.

In contrast to acoustic hearing aids, certain types of implantable auditory prostheses, sometimes referred to as implantable acoustic auditory prostheses, convert a received sound into output mechanical force (vibration) for delivery to the recipient. The vibrations are transferred through the recipient's, teeth, bone, and or other tissue to the cochlea. The vibrations cause movement of the cochlea fluid that generates nerve impulses resulting in perception of the received sound by the recipient. Acoustic auditory prostheses are suitable to treat a variety of types of hearing loss and may be prescribed for individuals who cannot derive sufficient benefit from acoustic hearing aids, cochlear implants, etc., or for individuals who suffer from stuttering problems. Implantable acoustic auditory prostheses include, for example, bone conduction devices, middle ear auditory prostheses (middle ear implants), direct acoustic stimulators (direct cochlear stimulators), or other partially or fully implantable auditory prosthesis that deliver vibrations to a recipient to directly or indirectly generate movement of the cochlea fluid.

SUMMARY

In one aspect, an implantable auditory prosthesis is provided. The implantable auditory prosthesis comprises a piezoelectric transducer configured to be implanted in a recipient and comprising at least one piezoelectric element configured to deform in response to application of electrical signals thereto so as to generate vibration for delivery to the recipient, and one or more components mechanically and electrically connected to the piezoelectric element and are configured to generate additional vibration for delivery to the recipient.

In another aspect, an implantable auditory prosthesis is provided. The implantable auditory prosthesis comprises a transducer comprising at least one bender element configured to generate vibration according to sound signals received by the device, one or more components mechanically and electrically connected to the bender element so as to generate additional vibration, and a body interface configured to deliver vibration generated by the bender element and the one or more components to a recipient.

In another aspect, a method for rehabilitating the hearing of a recipient is provided. The method comprises delivering electrical signals representative of sound to at least one piezoelectric element of a piezoelectric transducer so as to deform the piezoelectric element; generating, based on the deformation of the piezoelectric element, oscillation of one or more components mechanically and electrically coupled to the piezoelectric element; and delivering, to the recipient, vibration generated by the deformation of the piezoelectric element and the oscillation of the one or more components.

BRIEF DESCRIPTION OF THE DRAWINGS

Embodiments of the present invention are described herein in conjunction with the accompanying drawings, in which:

FIG. **1** is a diagram illustrating a middle ear auditory prosthesis in accordance with embodiments presented herein;

FIG. **2** is a diagram illustrating another middle ear auditory prosthesis in accordance with embodiments presented herein;

FIG. **3** is a cross-sectional schematic diagram of a transducer assembly in accordance with embodiments presented herein;

FIG. **4** is a diagram illustrating piezoelectric material forming part of a piezoelectric transducer;

FIG. **5** is a cross-sectional schematic diagram of another transducer assembly in accordance with embodiments presented herein; and

FIG. **6** is a flowchart of a method in accordance with embodiments presented herein.

DETAILED DESCRIPTION

Embodiments of the present invention are generally directed to an implantable auditory prosthesis that comprises a transducer configured to be implanted in a recipient. The transducer comprises at least one bender element (e.g., piezoelectric element, magnetorestrictive element, etc.) that is configured to deform in response to application of an electrical signal thereto so as to generate vibration for delivery to the recipient. One or more components are mechanically coupled to the bender element and are configured to enhance and/or generate additional vibration for delivery to the recipient. In certain embodiments, the one or more components mechanically coupled to the bender element comprise an inductor coil operating as a counter-mass. The inductor coil may be configured to drive another mass (e.g., a magnet) so as to operate as an active vibration generation system (e.g., electromagnetic transducer).

There are different types of auditory prostheses that may be partially or fully implanted into a recipient, including implantable acoustic auditory prostheses such as bone conduction devices (e.g., percutaneous, transcutaneous, etc.), middle ear auditory prostheses, direct acoustic stimulators, etc. It is to be appreciated that embodiments presented herein may be used in connection with any of the above or other implantable auditory prostheses. However, merely for ease of description, embodiments of the present invention are primarily described herein with reference to a middle ear auditory prosthesis.

FIG. **1** is a schematic diagram illustrating a middle ear auditory prosthesis **100** in accordance with embodiments presented herein. In general, the middle ear auditory prosthesis **100** is configured to generate movement of one or more of the recipient's middle ear bones (i.e., the malleus, incus, and stapes, collectively referred to as the "ossicles") based on a received sound signal.

The middle ear auditory prosthesis **100** includes an external component **102** and an implantable component **104**. The middle ear auditory prosthesis **100** of FIG. **1** is referred to as an "active" device because the implantable component **104** includes a subcutaneously implanted floating mass actuator/transducer **130**. In other words, the active vibration generation component of the middle ear auditory prosthesis **100** is implanted within the recipient, rather than positioned externally. The middle ear auditory prosthesis **100** of FIG. **1** is also referred to as a "transcutaneous" device because the device includes the external component **102** that provides data for use in stimulating the hearing of a recipient.

The external component **102** is directly or indirectly attached to the body of the recipient and typically comprises an external coil **108** and, generally, a magnet (not shown in FIG. **1**) fixed relative to the external coil **108**. The external component **102** also comprises one or more sound input elements **112** (e.g., microphones, telecoils, etc.) for receiving sound signals, and a sound processing unit **106**. The sound processing unit **106** is electrically connected to the external coil **108** via a cable or lead **110**.

In the embodiment of FIG. **1**, the sound processing unit **106** is a behind-the-ear sound processing unit. The sound processing unit **106** may include, for example, a power source (not shown in FIG. **1**) and a sound processor (also not shown in FIG. **1**). The sound processor is configured to process electrical signals generated by the sound input element **112**.

As noted, FIG. **1** illustrates an example in which middle ear auditory prosthesis **100** includes an external component **102** with an external sound processor. It is to be appreciated that the use of an external component is merely illustrative and that the techniques presented herein may be used in arrangements having an implanted sound processor, an implanted microphone, and/or an implanted power source (battery). It is also to be appreciated that the individual components referenced herein, e.g., sound input elements, the sound processor, etc., may be distributed across more than one device, e.g., two middle ear auditory prostheses, and indeed across more than one type of device, e.g., a middle ear auditory prosthesis and a consumer electronic device or a remote control of the middle ear auditory prosthesis.

The implantable component **104** comprises an implantable coil **116** and, generally, a magnet (not shown) fixed relative to the internal coil **116**. The magnets adjacent to the external coil **108** and the implantable coil **116** facilitate the operational alignment of the external and implantable coils. The operational alignment of the coils enables the external coil **108** to transcutaneously transmit/receive power and data to/from the implantable coil **116**. More specifically, in certain examples, external coil **108** transmits electrical signals (e.g., power and data) to implantable coil **116** via a transcutaneous radio frequency (RF) link **114**. External coil **108** and implantable coil **116** are typically wire antenna coils comprised of multiple turns of electrically insulated single-strand or multi-strand platinum or gold wire. The electrical insulation of implantable coil **116** is provided by a flexible silicone molding. It is to be appreciated that various other types of energy transfer, such as infrared (IR), electromagnetic, capacitive and inductive transfer, may be used to transfer the power and/or data from external component **102** to implantable component **104** and that FIG. **1** illustrates only one example arrangement.

The implantable coil **116** is electrically connected to an electronics assembly **122** that is electrically connected to a transducer assembly **120** via a lead (e.g., two-wire lead) **124**. The transducer assembly **120** includes a floating mass transducer which, in the embodiments of FIG. **1**, is a piezoelectric transducer **130** configured to generate mechanical output force (vibration) for delivery to the recipient's tissue (e.g., bone or other tissue).

More specifically, the electronics assembly **122** uses the data received from the external component **102** to generate electrical signals (transducer drive signals) that are delivered to a piezoelectric element (e.g., multilayer piezoelectric element) of the piezoelectric transducer **130**. When delivered to the piezoelectric transducer **130**, the transducer drive signals cause the piezoelectric transducer **130** to generate vibration which is transferred through a recipient's tissue and/or bone to the cochlea, thereby causing generation of nerve impulses that result in the perception of the sound signals received by the sound input element **112**. The transducer assembly **120** also includes one or more components **132** mechanically coupled to the piezoelectric transducer **130**. As described further below, the one or more components **132** are configured to generate additional vibration for delivery to the recipient via a body interface **160**.

It is to be appreciated that the piezoelectric transducer **130** and the one or more components **132** are positioned within a housing **134** of transducer assembly **120**. As such, the piezoelectric transducer **130** and the one or more components **132** are generally shown in FIG. **1** using dashed lines.

It is to be appreciated that acoustic auditory prostheses in accordance with embodiments of the present invention may have a number of different arrangements. For example, FIG. **2** illustrates a monolithic arrangement for a middle ear auditory prosthesis **200** where the external component **102** (FIG. **1**) operates with an alternative implantable component **204**. The implantable component **204** comprises an implantable coil **216** electrically connected to an electronics assembly (not shown in FIG. **2**) that is embedded within a transducer assembly **220** (i.e., the electronics assembly and the transducer assembly **220** are disposed within the same housing). In certain embodiments, the transducer assembly **220** includes a piezoelectric transducer **230** that is configured to generate vibration for delivery to the recipient via body interface **260**. Similar to the embodiment of FIG. **1**, the transducer assembly **120** also includes one or more components **232** mechanically coupled to the piezoelectric transducer **230**. As described further below, the one or more components **232** are configured to generate additional vibration for delivery to the recipient.

Similar to the embodiment of FIG. **1**, the piezoelectric transducer **230** and the one or more components **232** are positioned within a housing **234** of transducer assembly **220**. As such, the piezoelectric transducer **230** and the one or more components **232** are generally shown in FIG. **2** using dashed lines.

It is to be appreciated that the use of the external component **102**, as shown in FIGS. **1** and **2**, is merely illustrative and that other embodiments may use alternative external components or no external components, alternate body interfaces to contact various structures of the middle ear or inner ear, etc. For example, one alternative embodiment may use a coil sound processing unit having, for example, a generally cylindrical shape. In such an embodiment, the sound input element, sound processor, external coil, and external magnet are disposed within (or adjacent to) the same housing configured to be worn at the same location as where an external coil is traditionally located. In another embodiment, the components forming part of external component **102** (FIGS. **1** and **2**) are implanted. That is, further embodiments may use an arrangement having an implanted sound processor, an implanted microphone, and/or an implanted power source (battery), etc.

FIG. **3** is a cross-sectional schematic view of a transducer assembly **320** in accordance with embodiments of the present invention. The transducer assembly **320** comprises a hermetic housing **340** that forms a hermetically sealed enclosure for the transducer assembly **320**. In certain embodiments, the hermetic housing **340** may be formed from ceramic, titanium or other biocompatible metals, etc.

In accordance with certain embodiments presented herein, the transducer assembly **320** is configured to be miniaturized relative to conventional devices so as to fit within a recipient's middle ear cavity. The hermetic housing **340** contributes to the total size of the transducer assembly **320**. As such, embodiments presented herein may use a biocompatible coating/plating technique to reduce the size of the hermetic housing **340** (e.g., epoxy like coating, gold or other metal plating, etc.)

The hermetic housing **340** includes a hermetic feedthrough **342** comprising a plurality of feedthrough pins **344**. The hermetic feedthrough **342** enables the transducer assembly **320** to be electrically connected to an electronics assembly (not shown in FIG. **3**) via a lead cable **346**. The lead cable **346** includes one or more conductors (wires) **348** that connect to the feedthrough pins **344** and extend to the electronics assembly. In certain embodiments, the lead cable **346** may have a flexible construction that can be extended, for example, as a recipient's skull grows. Such a configuration may be advantageous for implantation of devices in children.

As noted above, the use of a separate electronics assembly is merely illustrative and in alternative embodiments the components of electronics assembly may be integrated with the components of the transducer assembly **320**. In certain such embodiments, the hermetic feedthrough **342** could be omitted.

The transducer assembly **320** comprises a floating mass transducer which, in the embodiments of FIG. **3**, is a piezoelectric transducer **330** that includes a piezoelectric element **350**. As shown in FIG. **4**, the piezoelectric element **340** comprising one or more layers of piezoelectric material **342** (e.g., lead zirconium titanate (PZT), barium titanate (BaTiO30), zirconium (Zr), quartz (SiO2), Berlinite (AlPO4), Gallium orthophosphate (GaPO4), Tourmaline, etc.). The pieces of piezoelectric material **342** are capacitive elements that are configured to convert electrical signals applied thereto into a mechanical deformation (i.e. expansion or contraction) of the material. That is, by applying a voltage over the piezoelectric material **342**, the piezoelectric material deforms (i.e., the mechanical position state of the piezoelectric material will change from an initial state) to generate an output force (F_{out}). As such, the electrical energy applied to the piezoelectric material **342** is, at least in part, transferred into mechanical energy.

The amount of deformation (ΔX_{out}) of the piezoelectric material **342** in response to an applied electrical signal may depend on, for example, the inherent properties of the material, orientation of the electric field with respect to the polarization direction of the piezoelectric material, geometry of the piezoelectric material, etc. Reinforced mechanical motion may be produced by grouping identical layers of electrodes interleaved with piezoelectric material. In particular, the segments may be interconnected mechanically in series (sum of mechanical forces) and connected electrically in parallel so as to produce the mechanical motion.

Returning to FIG. **3**, transducer drive signals (electrical signals) are applied to the piezoelectric element **350** via one of the conductive pads **354** attached to a first end **356**(A) of the piezoelectric element **350**. The conductive pads **354**, which are electrically connected to the feedthrough pins **344** via wire conductors **355**, receive the electrical signals via the wires **348** of lead cable **346**. The electrical signals may be alternating current (AC) signals that, when applied to the piezoelectric element **350**, cause a second end **356**(B) of the piezoelectric element **350** to oscillate in the directions shown by bi-directional arrow **358**. With AC signals, the direction current periodically reverses/alternates and a first direction of the current flow may cause the piezoelectric element **350** to deform in a first direction, while the second direction of the current flow may cause the piezoelectric element **350** to deform in a second direction that is opposite to the first direction, thereby creating the oscillation of second end **356**(B) of the piezoelectric element **350**.

The piezoelectric element is mechanically coupled to the hermetic housing **340** which is substantially rigidly attached to the recipient via an interface **360** with the recipient's body. As such, the oscillation of second end **356**(B) generates vibration that is delivered to the recipient via body interface **360**. Body interface **360** may take a number of different forms for attachment to various anatomical structures of the middle ear or inner ear (e.g., ossicles in the middle ear, round window, oval window, etc.). In the example of FIG. **3**, the body interface **360** is a clip mechanism for attachment to the recipient's middle ear bones (e.g., the recipient's incus). As such, in this specific example, oscillation of the piezoelectric element **350** generates movement of the recipient's middle ear bones.

It is to be appreciated that the body interface **360** shown in FIG. **3** is merely illustrative and that other body interfaces may be used in alternative arrangements. For example in one alternative embodiment the body interface **360** may comprise a coupling and bone screw. In still other embodiments, the body interface may comprise a region of the hermetic housing **340** attached to the recipient using bone cement or another fixation mechanism.

As noted, the oscillation of the piezoelectric element **350** generates vibration that is delivered to the recipient. In the embodiment of FIG. **3**, one or more components are included in the transducer assembly **320** to increase the vibration that is delivered to the recipient. More specifically, in the embodiment of FIG. **3** a component in the form of an inductor coil **362** is mechanically coupled to the second end **356**(B) of the piezoelectric element **350**. Due to the mechanical connection with piezoelectric element **350**, the inductor coil **362** will move in response to the oscillation of the piezoelectric element **350**. That is, when second end **356**(B) of the piezoelectric element **350** oscillates in the direction of arrow **358**, the inductor coil **362** will also oscillate in the direction shown by arrow **358**. As such, the inductor coil **362**, which is mechanically coupled to the piezoelectric element **350**, is configured to generate additional vibration for delivery to the recipient (i.e., generate additional vibration in response to oscillation of the piezoelectric element **350**).

In general, the inductor coil **362** comprises a plurality of wire loops **366** that collectively have a large mass relative to that of piezoelectric element **350**. As such, the additional mechanical force generated by the inductor coil **362** may be greater than the mechanical force generated by oscillation of the piezoelectric element **350** alone. In essence, the inductor coil **362** operates as a counter-mass component to increase the vibration generated by the transducer assembly **320**.

The inductor coil **362** may be mechanically connected to the second end **356**(B) of piezoelectric element **350** in a number of different manners. In the specific arrangement of FIG. **3**, a support bracket **363** is attached to the second end **356**(B) and to a plurality of the wire loops **366**.

In addition to the mechanical connection, the inductor coil **362** is also electrically connected to the piezoelectric element **350**. Conductive pads **364** are attached near the second end **356**(B) of the piezoelectric element **350** and are electrically connected to opposing ends of the inductor coil **362** (i.e., the wire loops **366** disposed at the opposing ends of the inductor coil). This electrical connection between the piezoelectric element **350** and the inductor coil **362** enables the inductor coil **362** to operate as an energy recovery element that is configured to extract non-used energy from the piezoelectric element **350** and to store the non-used energy for subsequent use by the piezoelectric element.

More specifically, the piezoelectric element **350** is a capacitive load that builds up or releases electrical charge following the raising or descending slope of incoming drive signals. In operation, the electrical connection between the inductor coil **362** and the piezoelectric element **350** enables the inductor coil **362** to extract and store energy that is not used by the piezoelectric element **350** to effect deformation of the second end **356**(B). The extracted and stored energy may then be added back to the piezoelectric element **350** to effect further deformation (e.g., deformation in an opposite direction). As such, the inductor coil **362** is sometimes referred to herein as energy recovery inductor **362**.

In summary, FIG. **3** illustrates an arrangement in which at least one inductor coil **362** is mechanically and electrically connected to the piezoelectric element **350**. The inductor coil **362** forms part of a continuous electrical circuit with the piezoelectric element **350** and is a dual-function component (i.e., a component that operates to increase the vibration generated by the transducer assembly **320** and to perform charge recovery).

FIG. **3** illustrates an example where the mechanical coupling between a piezoelectric element and one or more components contributes to the generation of additional vibration by the one or more components. FIG. **5** illustrates a further embodiment in which both the mechanical and the electrical connections between a piezoelectric element and one or more components contribute to the generation of additional output force by the one or more components. More specifically, FIG. **5** is a cross-sectional schematic view of a transducer assembly **520** in accordance with embodiments of the present invention. The transducer assembly **520** comprises a hermetic housing **540** that forms a hermetically sealed enclosure for the transducer assembly **520**. Similar to the example of FIG. **3**, the hermetic housing **540** may be formed from ceramic, titanium or other biocompatible metals, a biocompatible coating/plating, etc.

The hermetic housing **540** includes a hermetic feedthrough **542** that comprises a plurality of feedthrough pins **544**. The hermetic feedthrough **542** enables the transducer assembly **520** to be electrically connected to an electronics assembly (not shown in FIG. **3**) via a flexible lead cable **546** that may be similar to lead cable **346** of FIG. **3**. The lead cable **546** includes one or more conductors (wires) **548** that connect to the feedthrough pins **544** and extend to the electronics assembly. As noted above, the use of a separate electronics assembly is merely illustrative and in alternative embodiments the components of electronics assembly may be integrated with the components of the transducer assembly **520**. In certain such embodiments, the hermetic feedthrough **542** could be omitted.

The transducer assembly **520** comprises a floating mass transducer which, in the embodiments of FIG. **5**, is a piezoelectric transducer **530** that includes a piezoelectric element **350** that is substantially similar to piezoelectric element **350** of FIG. **3**. That is, the piezoelectric element **550** is formed from one or more layers of capacitive material that are configured to convert applied electrical signals into mechanical deformation (i.e. expansion or contraction) of the material. As such, electrical energy applied to the piezoelectric element **550** is, at least in part, transferred into mechanical energy.

Electrical signals (transducer drive signals) are applied to the piezoelectric element **550** via one of the conductive pads **554** attached to a first end **556**(A) of the piezoelectric element **550**. The conductive pads **554**, which are electrically connected to the feedthrough pins **544** via wire conductors **555**, receive the electrical signals via the wires **548** of lead cable **546**. The electrical signals may be AC signals that, when applied to the piezoelectric element **550**, cause a second end **556**(B) of the piezoelectric element **550** to oscillate in the directions shown by bi-directional arrow **558**. As noted above, since the direction of current periodically reverses/alternates in AC signals, a first direction of the current flow may cause the piezoelectric element **550** to deform in a first direction, while the second direction of the current flow may cause the piezoelectric element **550** to deform in a second direction that is opposite to the first direction, thereby creating the oscillation of second end **556**(B) of the piezoelectric element **550**. The oscillation of second end **556**(B) generates vibration that is delivered to the recipient via an interface **560** with the recipient's body.

Body interface **560** may take a number of different forms for attachment to various anatomical structures of the middle ear or inner ear (e.g., ossicles in the middle ear, round window, oval window, etc.). In the example of FIG. **5**, the body interface **560** is a clip mechanism for attachment to the recipient's middle ear bones (e.g., the recipient's incus). As such, in this specific example, oscillation of the piezoelectric element **550** generates movement of the recipient's middle ear bones.

As noted, the oscillation of the piezoelectric element **550** generates vibration for delivery to the recipient. In the embodiment of FIG. **5**, one or more components are included in transducer assembly **520** to increase the vibration delivered to the recipient. More specifically, in the embodiment of FIG. **5** a plurality of components forming an electromagnetic (EM) transducer **570** are mechanically coupled to the second end **556**(B) of the piezoelectric element **550**. In other words, in the arrangement of FIG. **5**, an electromagnetic transducer **570** is mechanically coupled to the piezoelectric transducer **530**

The electromagnetic transducer **570** comprises a magnet **572**, an inductor coil **562** comprising a plurality of wire loops **566**, and isolation members **574**. The magnet **572** is an elongate magnet having an elongate axis **576** extending there through. The wire loops **566** of inductor coil **562** are disposed at and/or around the ends of the magnet **572** generally perpendicular to elongate axis **576**. A support bracket **563** is provided that attaches to the second end **556**(B) of the piezoelectric element **550** and to a plurality of the wire loops **566**. In one specific embodiment, the support bracket **563** forms a sub-housing in which the magnet **572** is positioned. The isolation members **574** may be formed from a resiliently flexible material (e.g., rubber, silicone, etc.) that mechanically isolates the magnet **572** from the support bracket **563**.

It is to be appreciated that the electromagnetic transducer **570** may be mechanically connected to the second end **556**(B) of piezoelectric element **550** in a number of different manners. As such, the use of the support bracket **563** in FIG. **5** is merely illustrative of an example mechanical connection.

Due to the mechanical connection with piezoelectric element **550**, the electromagnetic transducer **570** will move in response to the oscillation of the piezoelectric element **550**. That is, when second end **556**(B) of the piezoelectric element **550** oscillates in the direction of arrow **558**, the electromagnetic transducer **570** will also oscillate in the direction shown by arrow **558**. As such, the electromagnetic transducer **570**, which is mechanically coupled to the piezoelectric element **550**, is configured to generate additional vibration for delivery to the recipient (i.e., generate additional vibration in response to oscillation of the piezoelectric element **550**).

In general, the wire loops **566**, magnet **572**, isolation members **574**, and support bracket **563** collectively have a mass that is large relative to that of the piezoelectric element **550**. As such, the additional mechanical force generated by the electromagnetic transducer **570** may be greater than the vibration generated by oscillation of the piezoelectric element **550** alone. In essence, the electromagnetic transducer **570** may operate as a counter-mass component to increase the vibration generated by the transducer assembly **520**.

As noted above, in addition to the mechanical connection, the electromagnetic transducer **570** is also electrically connected to the piezoelectric element **550**. Conductive pads **564**, which are attached near the second end **556**(B) of the piezoelectric element **550**, are electrically connected to opposing ends of the inductor coil **562** (i.e., the wire loops **566** disposed at the opposing ends of the inductor coil). This electrical connection between the piezoelectric element **550** and the inductor coil **562** enables the electromagnetic transducer **570** to be driven through the piezoelectric element **550**. That is, the electromagnetic transducer **570** is configured to be activated by the same signals delivered to the piezoelectric element **550**.

As noted above, in the arrangement of FIG. **5** current is delivered to the piezoelectric element **550**. A portion of the current is consumed at the piezoelectric element **550** to generate deformation of the piezoelectric element. However, at least some of the current passes through the piezoelectric element **550** to the inductor coil **562** via pads **564** at second end **556**(B). The current flows through the inductor coil **562** so as to cause the electromagnetic vibrator **570** to generate oscillation in the direction of arrow **588** that is separate from the oscillation generated by piezoelectric element **550**. More specifically, as the current flows through the inductor coil **562**, the magnet **572** will reciprocate generally along elongate axis **576**. The reciprocating movement of magnet **572** generates independent and supplementary vibration that may be delivered to the recipient through body interface **560**.

In such embodiments, the piezoelectric transducer **550** generates vibration (i.e., through oscillation of the piezoelectric element **550**) for delivery to the recipient and the electromagnetic transducer **570** generates vibration (i.e., through the reciprocating movement of magnet **572**) for delivery to the recipient. The vibration generated by the piezoelectric transducer **550** and the vibration generated by the electromagnetic transducer **570** are generally complementary/cooperative. As such, FIG. **5** illustrates an embodiment in which two transducers operating according to different activation principles (e.g., the piezoelectric effect and the electromagnetic affect) are mechanically and electrically coupled in a manner that enables the transducers to cooperate to generate vibration for delivery to a recipient.

In certain embodiments, the piezoelectric transducer **550** and the electromagnetic transducer **570** have different resonant frequencies. In such embodiments, the combined vibration of the piezoelectric transducer **550** and the electromagnetic transducer **570** creates an efficient system with a broader frequency range than devices that use only a piezoelectric transducer or an electromagnetic transducer **570**. For example, in one such embodiment the system may have a response characteristic with multiple maxima.

The electrical connection between the piezoelectric element **550** and the inductor coil **562** may also enable the inductor coil **562** to operate as an energy recovery element. More specifically, similar to the embodiment of FIG. **3**, the inductor coil **562** may be configured to extract and store energy that is not used by the piezoelectric element **550** to effect deformation of the second end **556**(B). The extracted and stored energy may then be added back to the piezoelectric element **550** to effect further deformation (e.g., deformation in an opposite direction). As such, the inductor coil **562** is sometimes referred to herein as energy recovery inductor **562**.

In summary, FIG. **5** illustrates an arrangement in which the electromagnetic transducer **570** is mechanically and electrically connected to a piezoelectric transducer **530**. The electromagnetic transducer **570** forms part of a continuous electrical circuit with the piezoelectric transducer **570** and is a multi-function component that can create additional vibration in multiple manners. In particular, the electromagnetic transducer **570** generates additional vibration as a result of the mechanical coupling to piezoelectric transducer **530** by operating as counter-mass component for the piezoelectric element **550**. Additionally, the electromagnetic transducer **570** operates as an active vibration generation system to generate supplementary vibration based on electrical signals received through the piezoelectric element **550**. Finally, the inductor coil **562** of the electromagnetic transducer **570** may operate as an energy recovery element that is configured to extract non-used energy from the piezoelectric element **550** and to store the non-used energy for subsequent use by the piezoelectric element.

FIG. **6** is a flowchart of a method **680** in accordance with embodiments of the present invention. Method **680** begins at **682** where electrical signals representative of sound are delivered to at least one piezoelectric element of a piezoelectric transducer so as to deform the piezoelectric element. At **684**, based on the deformation of the piezoelectric element, oscillation of one or more components mechanically coupled to the piezoelectric element is generated. At **686**, vibration generated by the deformation of the piezoelectric element and the oscillation of the one or more components is delivered to the recipient.

As noted above, embodiments presented herein are directed to use of one or more components as a counter-mass for a bender element, such as a piezoelectric element of a piezoelectric transducer. In general, an inductor coil is used as the counter-mass and the counter-mass may, in certain embodiments, drive another mass (e.g., a magnet). Such a system may have a small volume with increased mechanical and electrical efficiency. The combination of the piezoelectric transducer with an electromagnetic transducer, as described above, may utilize a single point of attachment

The invention described and claimed herein is not to be limited in scope by the specific preferred embodiments herein disclosed, since these embodiments are intended as illustrations, and not limitations, of several aspects of the invention. Any equivalent embodiments are intended to be within the scope of this invention. Indeed, various modifications of the invention in addition to those shown and described herein will become apparent to those skilled in the art from the foregoing description. Such modifications are also intended to fall within the scope of the appended claims.

What is claimed is:

1. An implantable auditory prosthesis, comprising:

a piezoelectric transducer configured to be implanted in a recipient and comprising at least one piezoelectric element configured to deform in response to application of electrical signals thereto so as to generate vibration for delivery to the recipient; and

one or more charge recovery inductors mechanically and electrically connected to the at least one piezoelectric element, wherein the one or more charge recovery inductors are configured to generate additional vibration for delivery to the recipient and are configured to extract non-used energy from the at least one piezoelectric element and to store the non-used energy for subsequent use by the at least one piezoelectric element.

2. The implantable auditory prosthesis of claim **1**, wherein the one or more charge recovery inductors are mechanically coupled to the at least one piezoelectric element so as to operate as a counter-mass to increase the vibration generated in response to deformation of the at least one piezoelectric element.

3. The implantable auditory prosthesis of claim **1**, wherein the implantable auditory prosthesis is a bone conduction device.

4. The implantable auditory prosthesis of claim **1**, wherein the implantable auditory prosthesis is a middle ear auditory prosthesis.

5. The implantable auditory prosthesis of claim **1**, further comprising:

a sound input element configured to receive one or more sound signals; and

an electronics module configured to generate the electrical signals based on the one or more sound signals so as to cause the piezoelectric transducer and the one or more charge recovery inductors to generate vibration resulting in perception by the recipient of the one or more sound signals.

6. The implantable auditory prosthesis of claim **5**, wherein at least one of the sound input element and the electronics module are implantable in the recipient.

7. The implantable auditory prosthesis of claim **1**, further comprising:

a body interface configured to deliver the vibration generated by the piezoelectric transducer and the one or more charge recovery inductors to the recipient.

8. The implantable auditory prosthesis of claim **7**, wherein the body interface is a clip mechanism for attachment to one or more middle ear bones of the recipient.

9. An implantable auditory prosthesis comprising:

a transducer comprising at least one bender element configured to generate vibration according to sound signals received by the implantable auditory prosthesis;

an electromagnetic transducer mechanically and electrically connected to the at least one bender element so as to generate additional vibration using electrical signals received via the at least one bender element; and

a body interface configured to deliver vibration generated by the at least one bender element and the electromagnetic transducer to a recipient.

10. The implantable auditory prosthesis of claim **9**, wherein the electromagnetic transducer is mechanically coupled to the at least one bender element so as to operate as a counter-mass to increase the vibration generated in response to deformation of the at least one bender element.

11. The implantable auditory prosthesis of claim **9**, wherein the implantable auditory prosthesis is a bone conduction device.

12. The implantable auditory prosthesis of claim **9**, wherein the implantable auditory prosthesis is a middle ear auditory prosthesis.

13. The implantable auditory prosthesis of claim **12**, further comprising:

a sound input element configured to receive the sound signals; and

an electronics module configured to generate the electrical signals based on the one or more sound signals so as to cause the piezoelectric transducer and the electromagnetic transducer to generate vibration resulting in perception by the recipient of the one or more sound signals.

14. The implantable auditory prosthesis of claim **9**, wherein the at least one bender element and the electromagnetic transducer have different resonant frequencies.

15. The implantable auditory prosthesis of claim **9**, wherein the at least one bender element is a piezoelectric element.

16. The implantable auditory prosthesis of claim **9**, wherein the at least one bender element is a magnetostrictive element.

17. A method for rehabilitating the hearing of a recipient, comprising:

delivering electrical signals representative of sound to at least one piezoelectric element of a piezoelectric transducer so as to deform the at least one piezoelectric element;

generating, based on the deformation of the at least one piezoelectric element, oscillation of at least one inductor coil mechanically and electrically coupled to the at least one piezoelectric element;

delivering, to the recipient, vibration generated by the deformation of the at least one piezoelectric element and the oscillation of the one at least one inductor coil;

extracting non-used energy from the at least one piezoelectric element;

storing the non-used energy for subsequent use by the at least one piezoelectric element; and

providing the stored non-used energy to the at least one piezoelectric element.

18. The method of claim **17**, further comprising:

receiving the sound via a sound input element implantable in the recipient.

19. A method for rehabilitating the hearing of a recipient, comprising:

delivering electrical signals representative of sound to at least one piezoelectric element of a piezoelectric transducer so as to deform the at least one piezoelectric element;

generating, based on the deformation of the at least one piezoelectric element, oscillation of one or more components mechanically and electrically coupled to the at least one piezoelectric element, wherein the one or more components comprise a magnet around which one or more inductor coils are positioned;

delivering, to the recipient, vibration generated by the deformation of the at least one piezoelectric element and the oscillation of the one or more components;

delivering the electrical signals representative of sound to the one or more inductor coils via the at least one piezoelectric element so as to generate motion of the magnet, wherein the motion of the magnet generates supplementary vibration; and

delivering the supplementary vibration to the recipient with the vibration generated by the deformation of the at least one piezoelectric element and the oscillation of the one or more components.

20. The method of claim **19**, further comprising:

receiving the sound via a sound input element implantable in the recipient.

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